Validation of the hadronic calibration of the ATLAS calorimeter with testbeam data corresponding to the pseudorapidity range 2.5<|eta|<4.0

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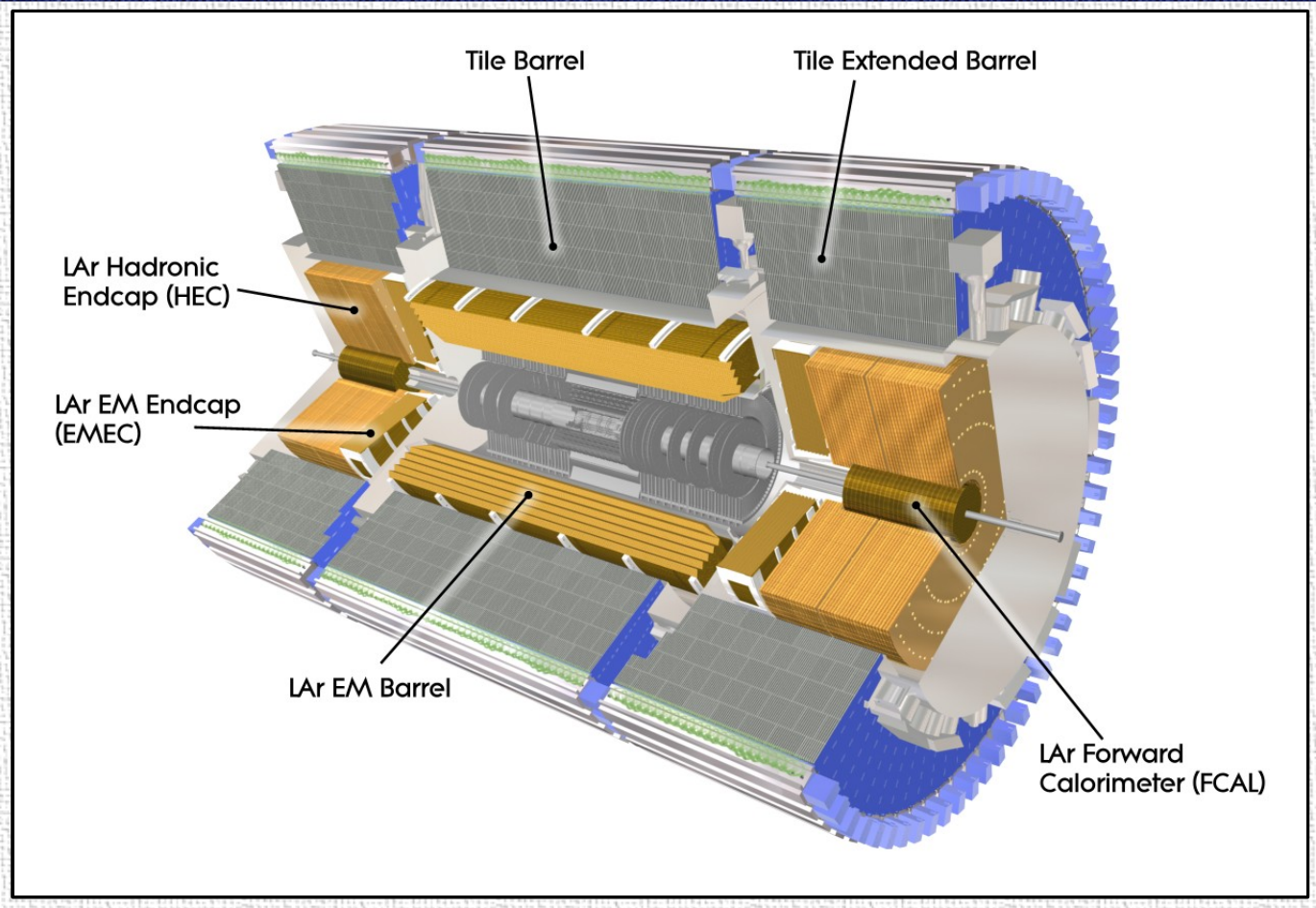
Outline

- Pions in the ATLAS calorimeter
- Local hadronic calibration schema
- Performance example for single pions in ATLAS simulations
- Setup for combined testbeam of LAr detectors in the forward region
- Measured Data & MC description
- Data/MC comparison for basic cluster quantities
- Basic performance for pions
- Conclusion

ATLAS calorimeters



Electromagnetic calorimeters:

acceptance	|η|<3.2
depth	~22X0
number of channels	173952
cluster noise	250 MeV
design goals	

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.7\%, \; E \; in \; GeV$$

$$nonlinearity < 0.1\%$$

Hadron and forward calorimeters:

acceptance	|η|<5.0
number of channels	19000
absorption length	9.7 – 13 λ
design goal for jets	

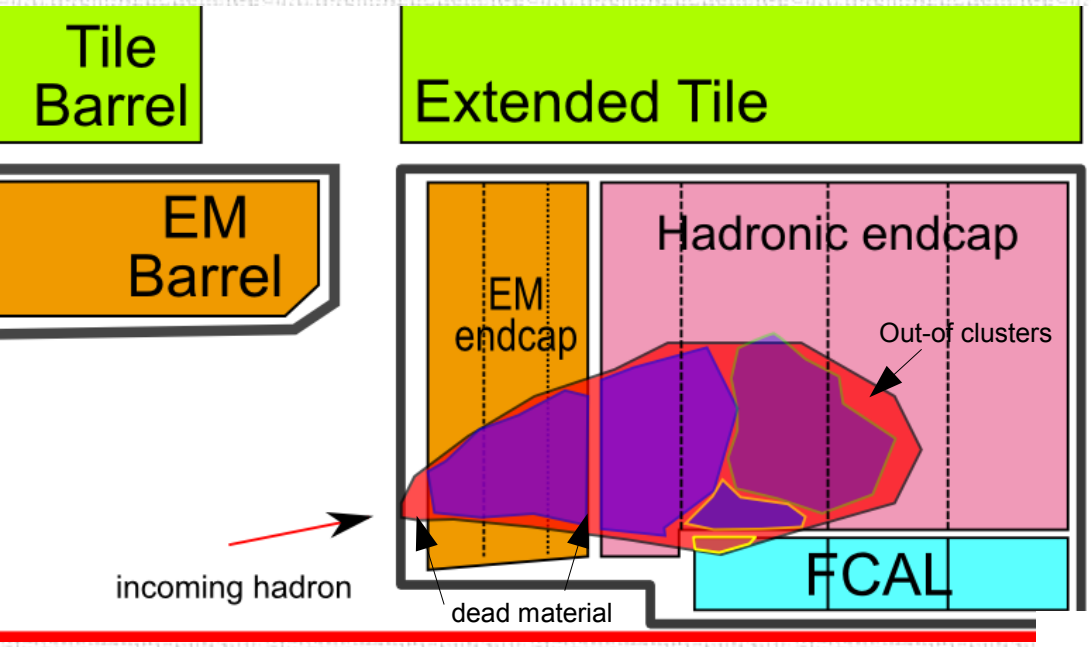
$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%, \; |\eta| < 3$$

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E}} \oplus 5\%, \; 3 < |\eta| < 5$$

$$nonlinearity < 2\%$$

- The jet energy scale is the major source of uncertainty for measurements of the top quark mass and inclusive jet cross sections

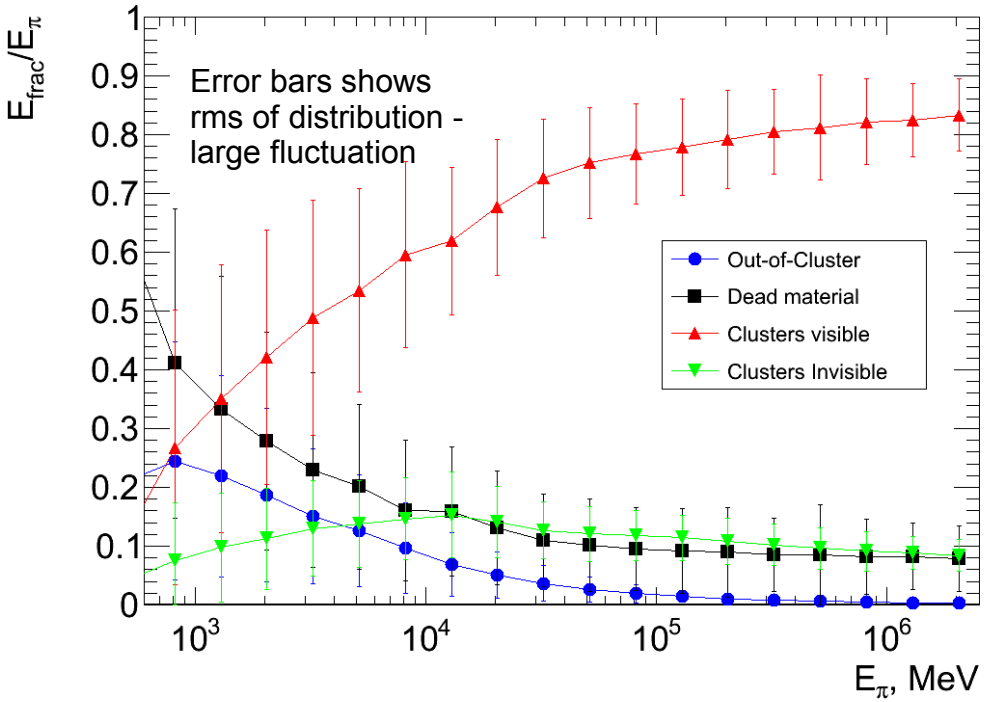
Pion in ATLAS calorimeter



- Factors responsible for nonlinearity and resolution degradation of hadrons
  - ➔ e/h>1 for each calorimeter system (invisible energy)
  - ➔ energy in non-instrumented regions
  - ➔ energy outside of any reconstructed calorimeter objects (clusters)

- For 10 GeV pions at η~2.5
  - ➔ O(60%) - energy in reconstructed clusters
  - ➔ O(15%) - invisible energy in clusters
  - ➔ O(15%) - energy in dead material
  - ➔ O(10%) - out-of-cluster energy
  - ➔ contributions depend on pion energy and are the subject of large fluctuations (see right-hand plot)

Calibration techniques are used to recover linearity and improve resolution.



Local hadronic calibration schema

- Calibration of topological clusters to particle level
  - ➔ Based on single pion simulations & GEANT4 truth energy deposits

3-d topological clusters with cells at e.m. scale.

- Cluster making starts from calorimeter cells at e.m. scale
  - ➔ Starting from seed $|E_{cell}|>4\eta_{noise}$, expanding in 3D around neighbors with $|E_{cell}|>2\eta_{noise}$, finally adding perimeter cells $|E_{cell}|>0$, split clusters around local maxima

classify clusters as e.m., had. or Unknown

- Classification to identify e.m. and non-e.m. parts of the shower
  - ➔ High average cell energy density $<\rho_{cell}>$ and small cluster depth λ_{center} denote e.m. nature of cluster

cluster calibration

- H1-style cells weighting for clusters classified as hadronic to account for non-compensation of the calorimeter

out-of-cluster correction

- Correction for energy deposited in calorimeter cells outside of any clusters due to noise thresholds

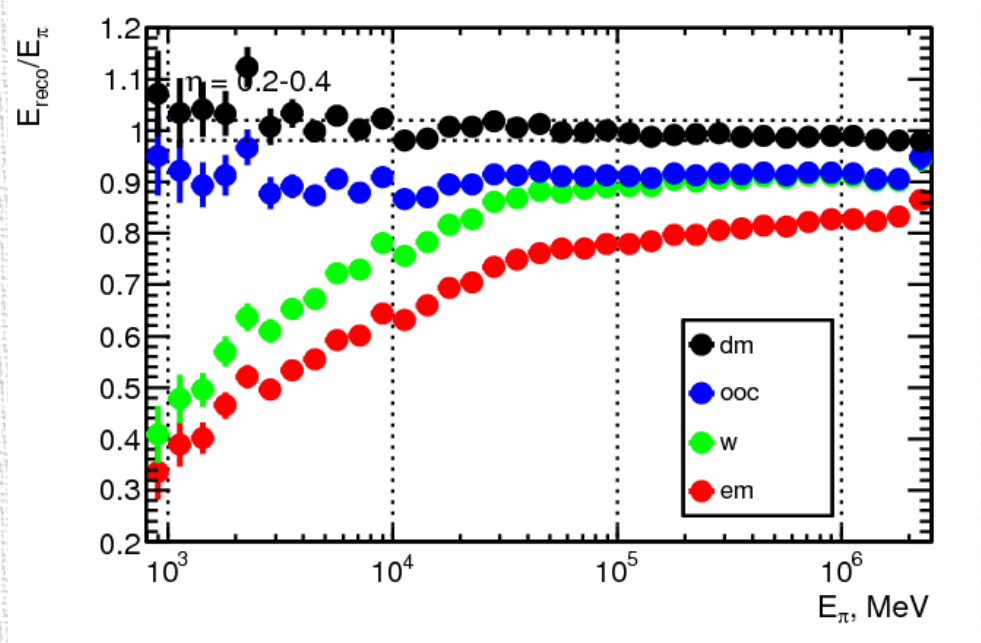
dead material correction

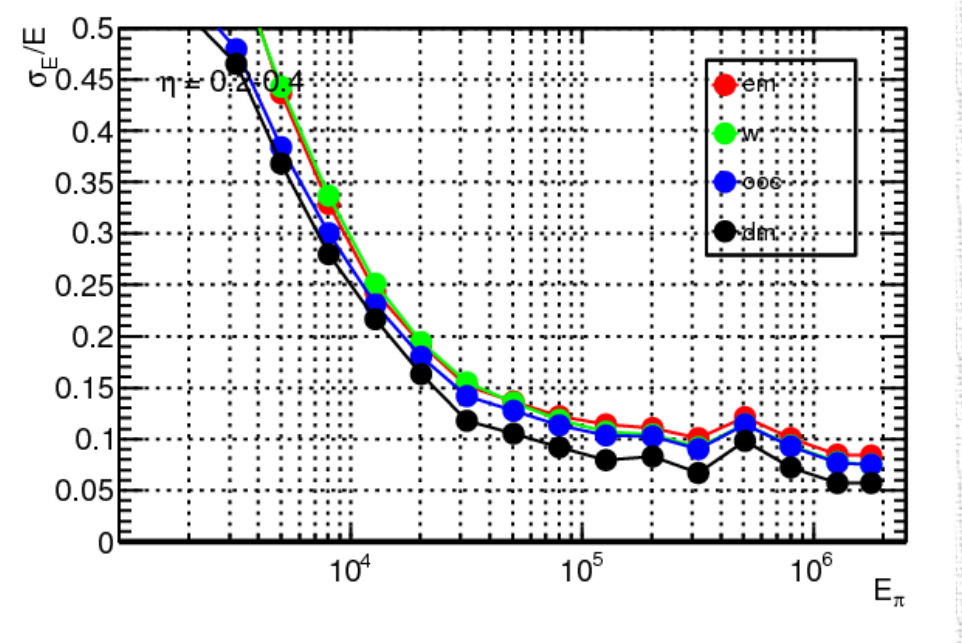
- Recovers lost energy in dead material in front and between calorimeter modules

calibrated clusters

- Clusters are calibrated to the particle level
  - ➔ Provides different jet algorithms with single input
  - ➔ Factorization of different effects

Single pion performance in ATLAS (Monte-Carlo)



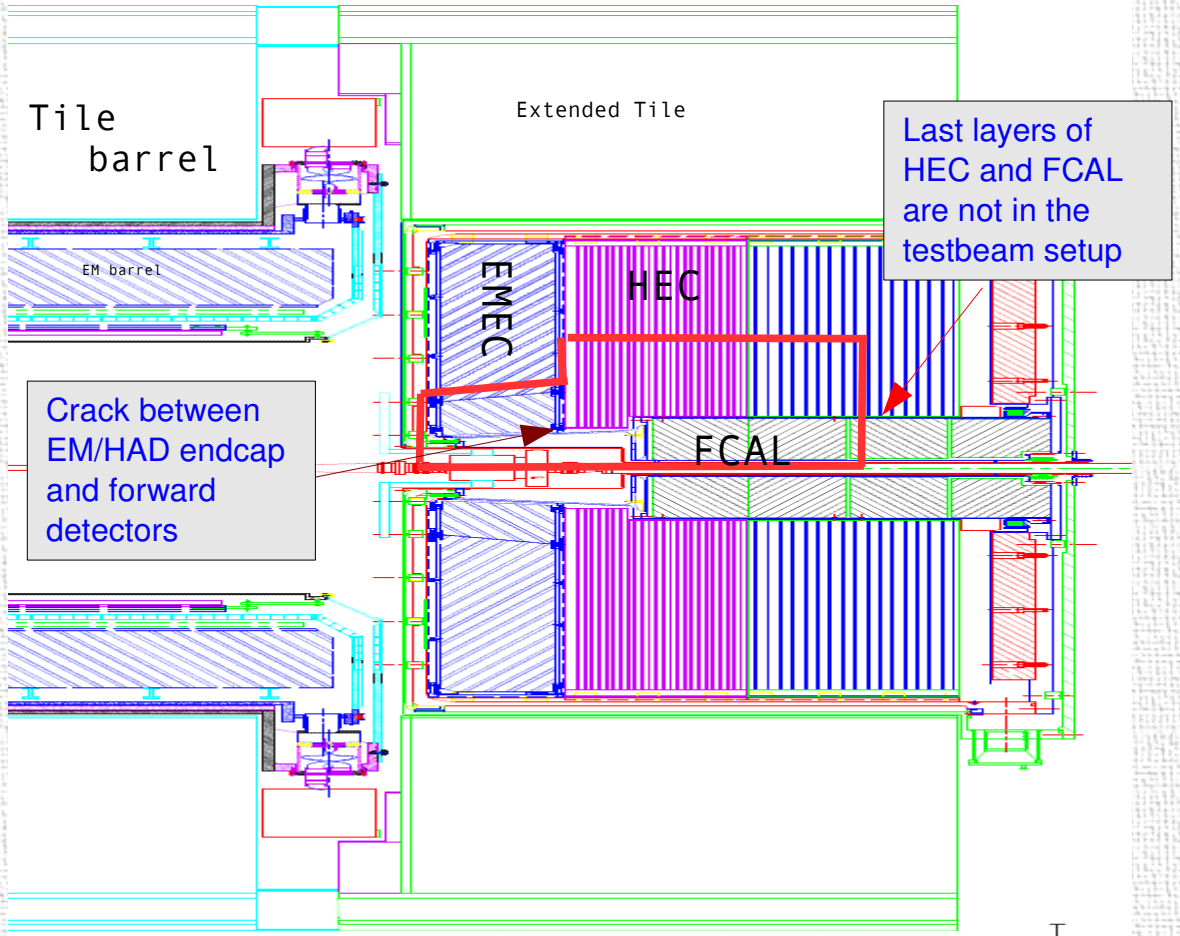


- Reconstructed pion energy (left) and energy resolution (right) as a function of initial pion energy after each step of local hadronic calibration
  - ➔ Each step of calibration improves linearity and resolution
  - ➔ After the last step (dead material correction) relative resolution was improved by ~30%, linearity is recovered within ±2%

Combined testbeam of LAr detectors in the forward region

- Combined test in 2004 of three LAr detectors in ATLAS forward region closed extensive program of beam tests started in 1996
  - NIM A 593 (2008) 323-342 describes performance for electrons/pions at e.m. scale
  - Subject of this talk – validation of ATLAS calorimeter reconstruction software (local hadronic calibration)

- One quadrant (module 0) of EMEC Inner Wheel
  - LAr + lead, accordion shape, 1/8 of whole wheel
  - Readout segmentation 0.1×0.1 ($\Delta\eta\times\Delta\varphi$)
- One quadrant in phi of HEC
  - LAr + parallel flat copper plates
  - Readout segmentation 0.1×0.1 ($\Delta\eta\times\Delta\varphi$) in outer, 0.2×0.2 in inner wheel
- One quadrant in phi of FCAL
  - LAr, EM part copper, HAD part tungsten alloy
  - Cylindrical electrodes parallel to the beam
  - Readout segmentation not projective, ~0.2×0.2



2D view of calorimeters with region tested marked by red line

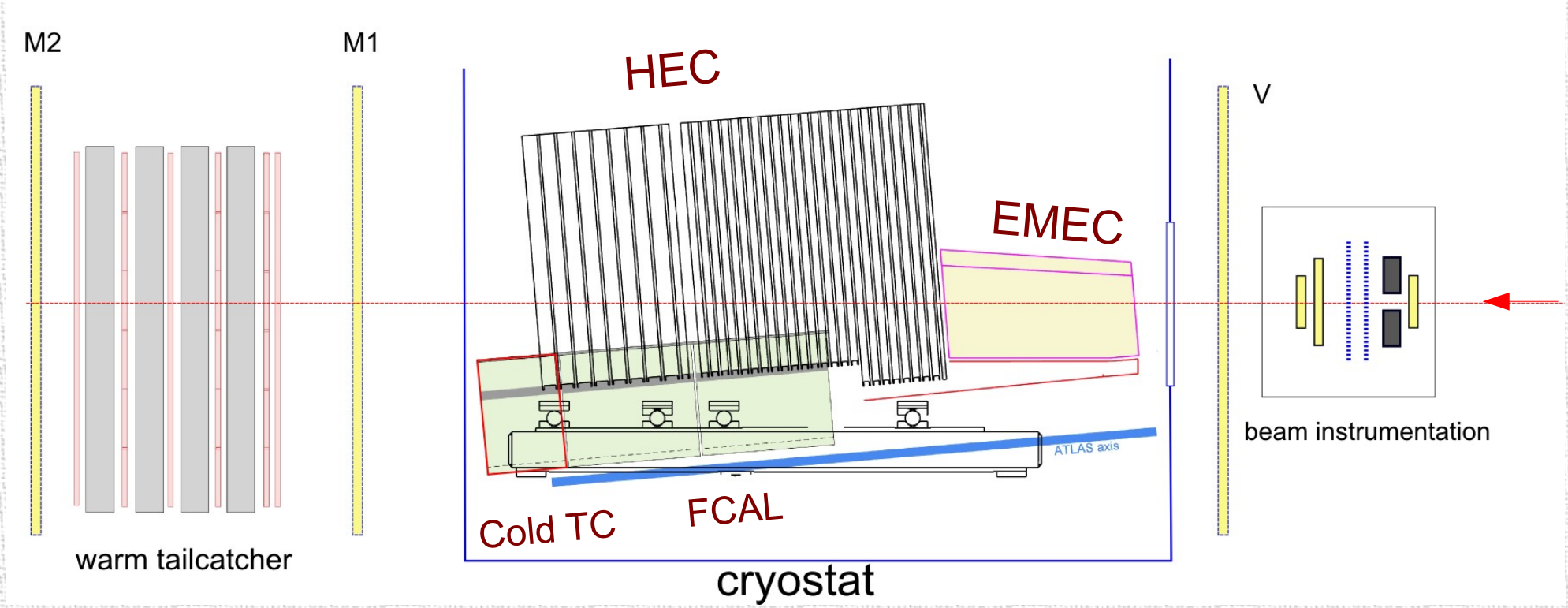
- Dead material between calorimeter and in front of FCAL as close as possible to nominal ATLAS situation.

Setup

- Setup placed in H1 cryostat in CERN North Hall, using the H6 beam line
  - ➔ Limited acceptance because of space constraint in H1 cryostat
  - ➔ The setup is tilted to be projective at η=2.8

Experimental setup includes

- Beam instrumentation: multiwire proportional chambers, scintillation counters, scintillation walls
- Cryostat with EMEC, HEC and FCAL calorimeter modules
- Warm and cold tail catchers to help identify longitudinal leakage



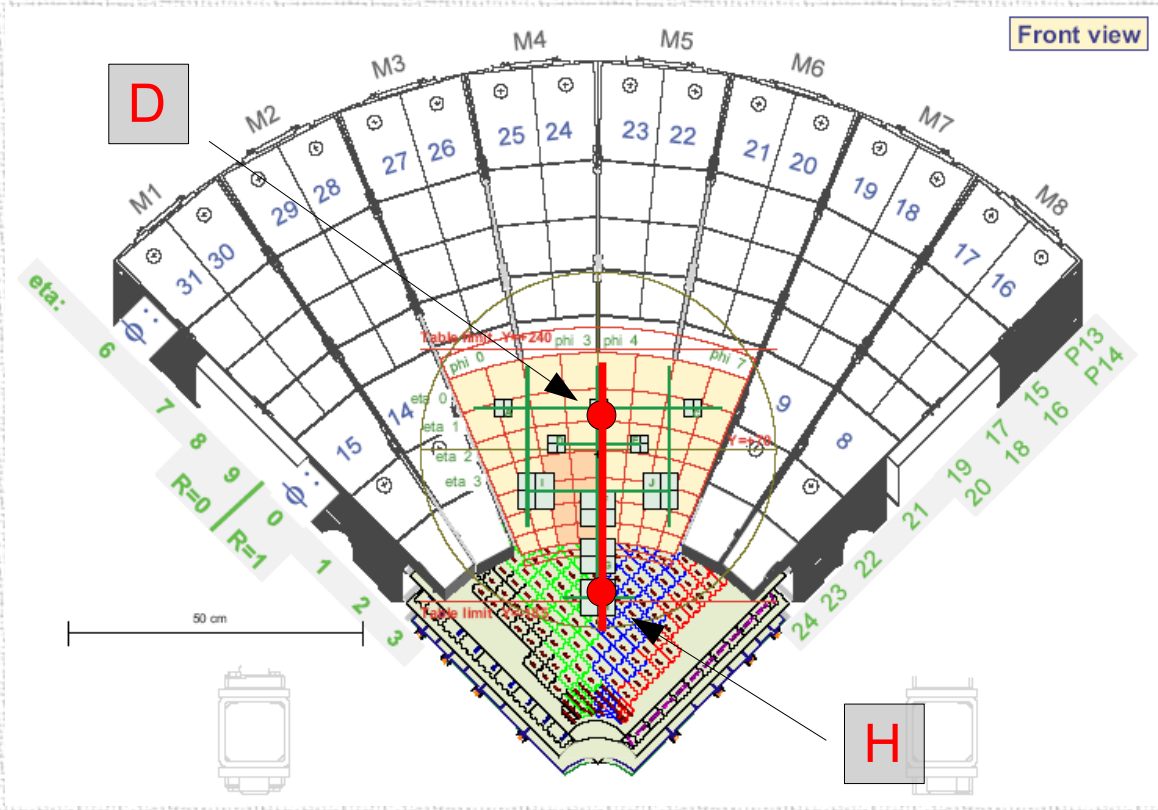
Data and Monte-Carlo

Data

- Various energy and position scans were performed for e-,π in the energy range 6GeV<E<200GeV with about 80 million triggers in total
  - ➔ Energy scans at a standard set of impact point (e.g. impact point D for the endcap area corresponding to η=2.8, impact point H for the forward area corresponding to η=3.65)
  - ➔ Position X,Y scans to cover full crack region

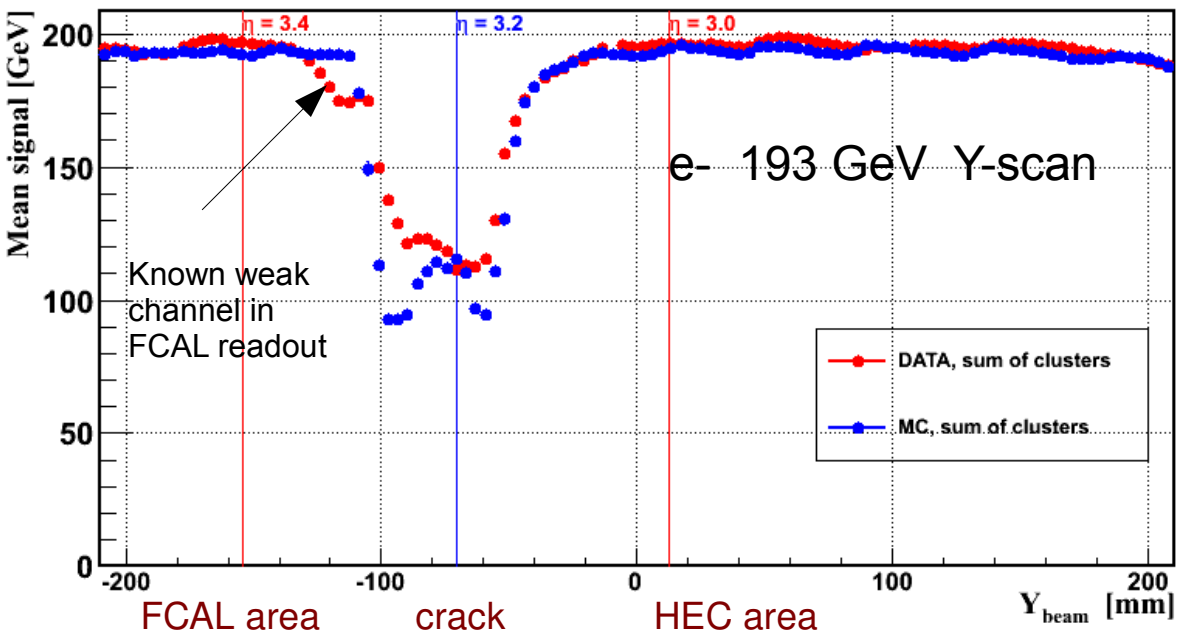
Monte-Carlo simulation

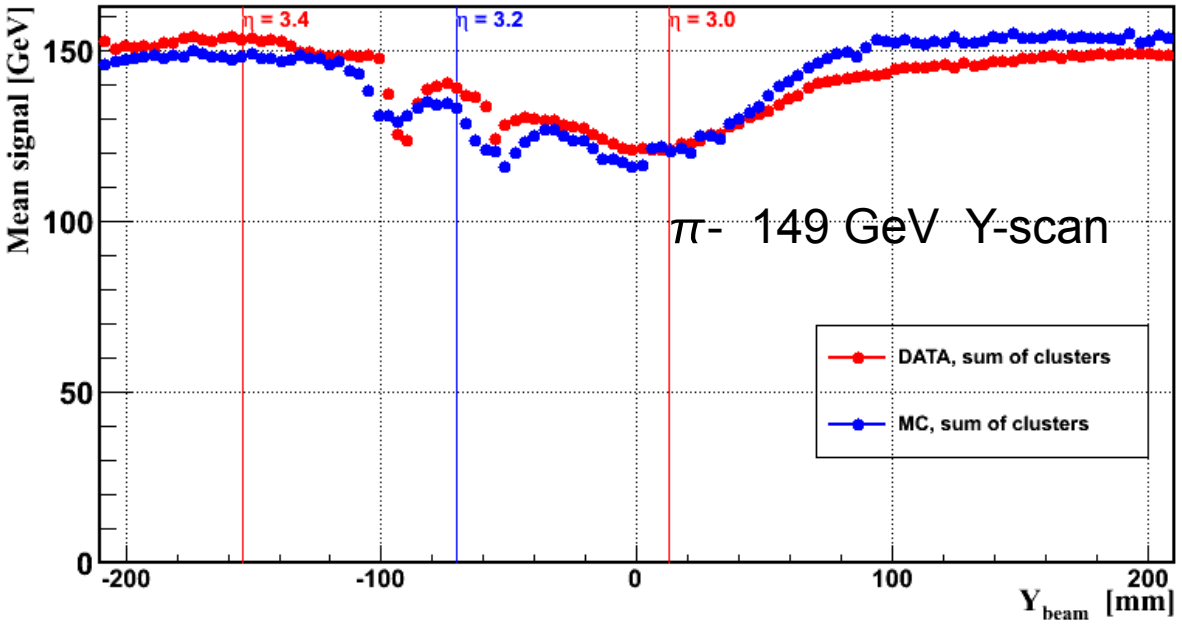
- Geant4 9.2.p00 with consistent description of testbeam setup
  - ➔ Range cut 30 μm
  - ➔ QGSP_BERT physics list
- Reconstruction with Atlas software release 15.3.0
  - ➔ hadronic calibration constants are corresponding to ATLAS geometry and not yet testbeam specific



Front view of the setup showing different beam impact points

Vertical scan with electrons and pions

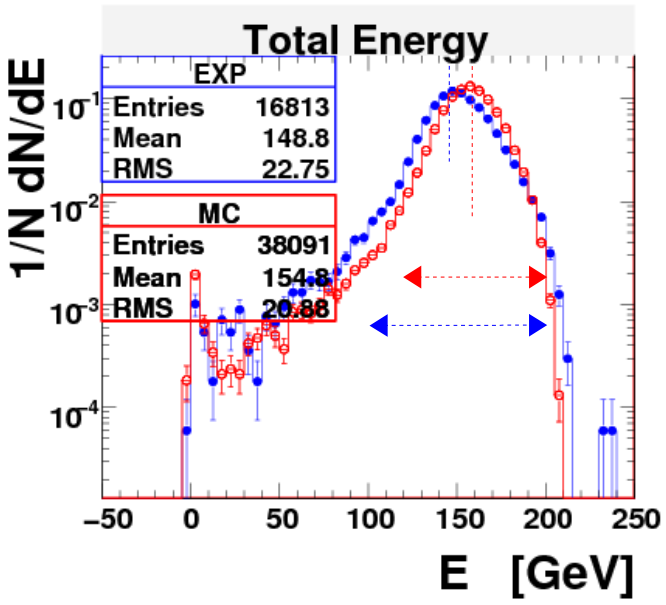


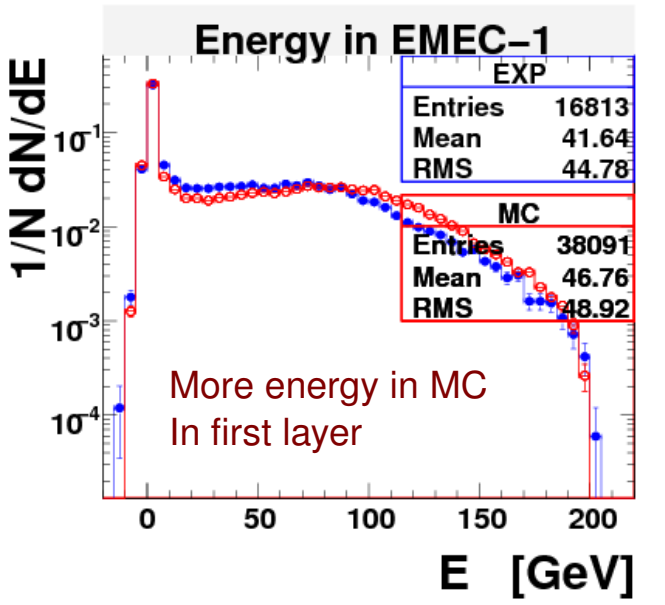


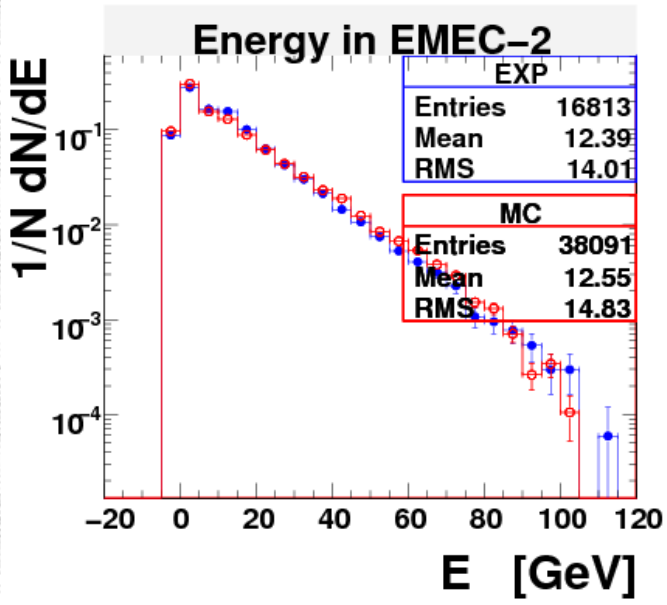
- Dependence of mean signal response at em-level on the beam position across endcap-forward region crack
  - ➔ Good check of MC geometry
- Electron scan (top plot)
  - ➔ Energy response quite nicely described outside crack (good em scale)
  - ➔ some discrepancy inside the crack (indication of clustering peculiarities there)
- Pion scan (bottom plot)
  - ➔ There are differences in MC versus DATA response – In forward region MC response is 3% lower, in endcap area it is 4% higher than in DATA
  - ➔ This is a QGSP_BERT issue

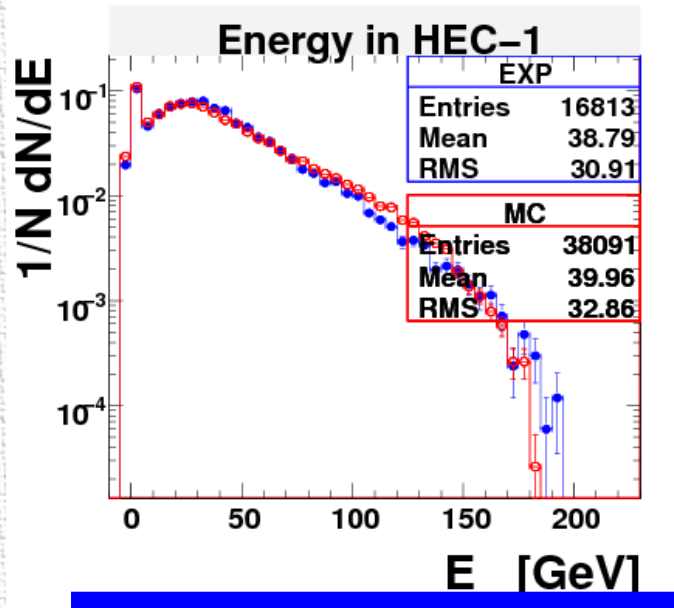
Energy in calorimeters in the endcap region (point D)

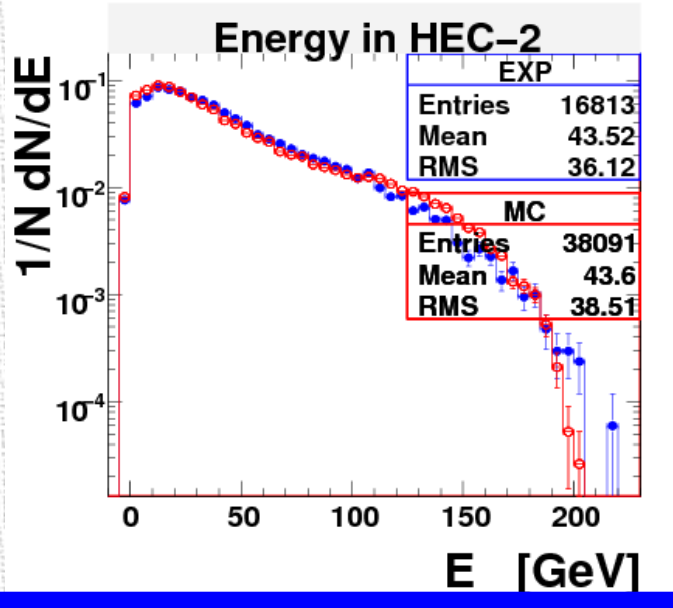
200 GeV pions at e.m. scale

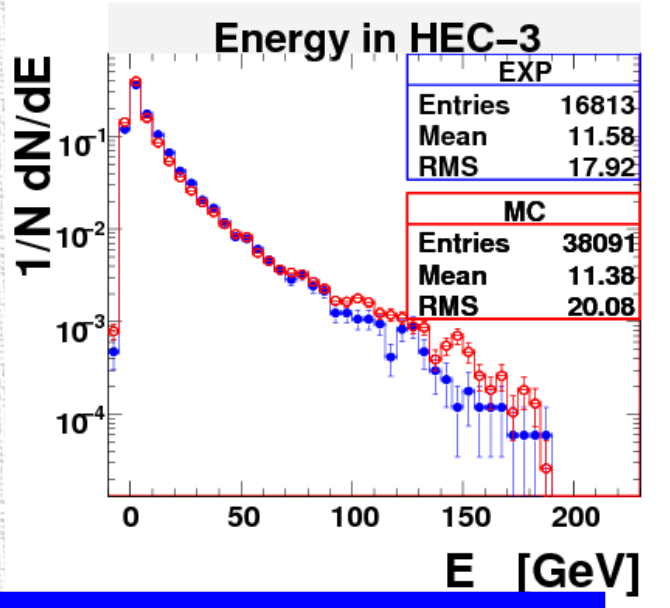












Monte-Carlo in comparison to the data: total energy deposited is larger, distribution is narrower.
More energy deposited in the first layer (EMEC-1) –hint that earlier showering in MC is present

Cluster moments

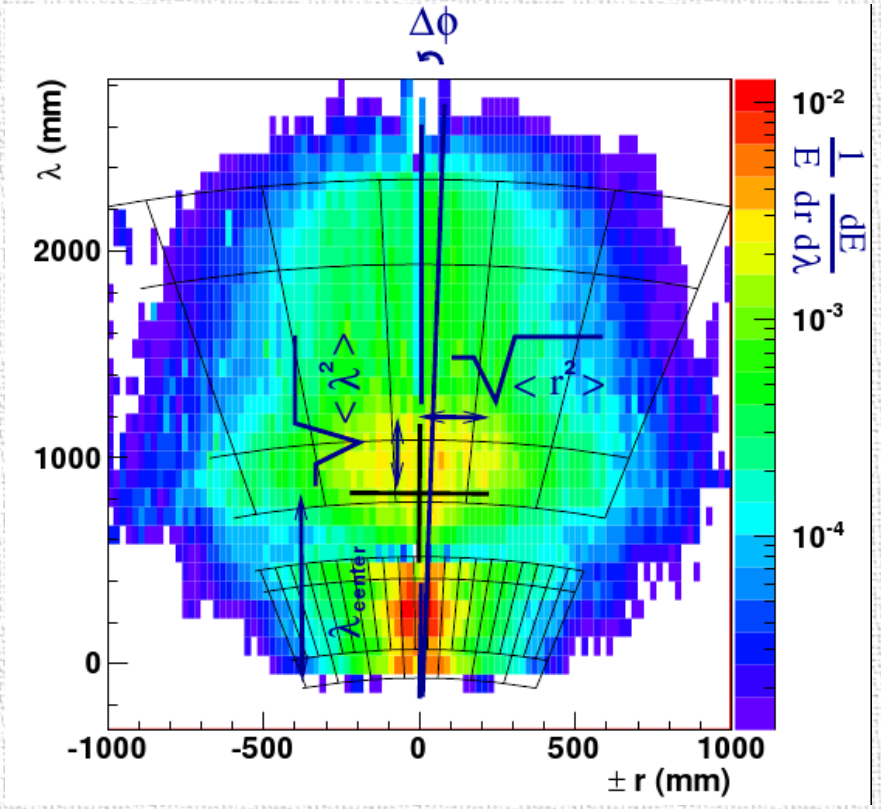
n_{th} cluster moment of x defined as

$$\langle x^n \rangle = \frac{1}{\sum_i E} \cdot \sum_i E_i \, x_i^n$$

looping over cells i

Cluster moments used in the local hadronic calibration

- First moment of energy density
- Shower depth λ_{center}
  - ➔ distance between shower center and calorimeter front face
- Shower length
  - ➔ sqrt() of second moment of λ (λ is distance of cell from shower center)
- Shower width
  - ➔ sqrt() of second moment of r, where r is distance of cell from shower axis
- Isolation moment
  - ➔ Fraction of cells on the outer cluster perimeter which are not included in any other cluster

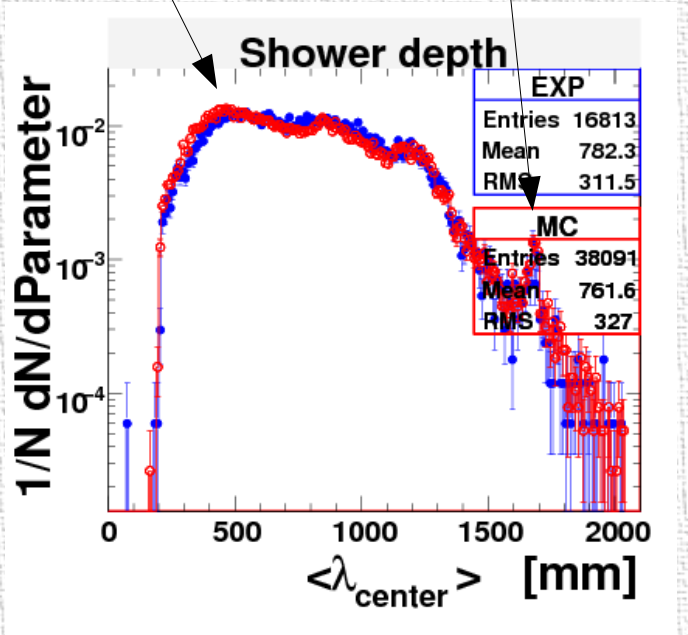


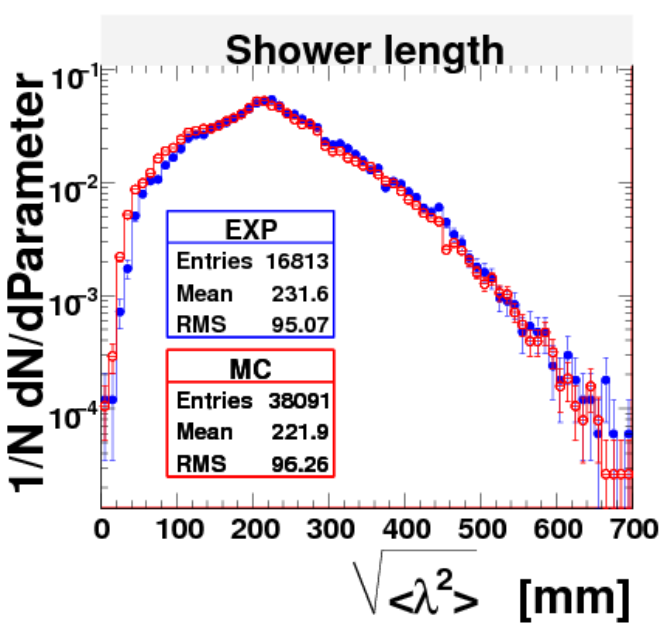
Cluster moments for the endcap region

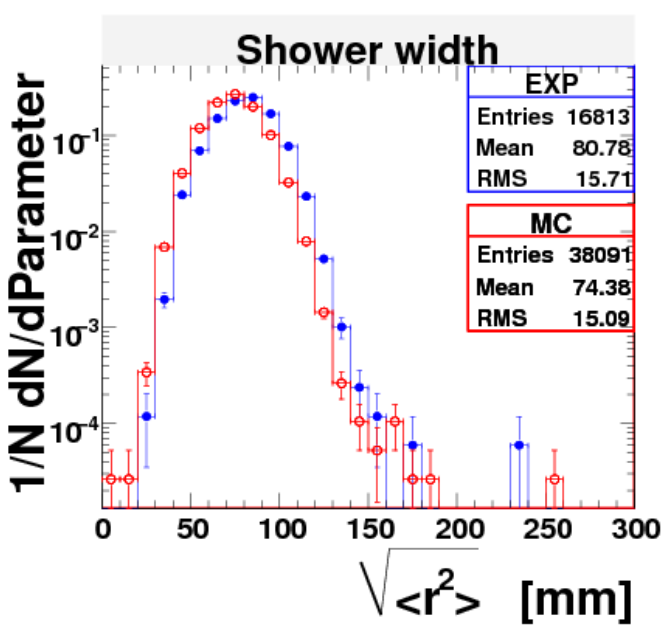
- Comparison of shower depth (left), shower length (center) and shower width (right) in Monte-Carlo and data
  - ➔ 200 GeV pions
  - ➔ shower starts slightly earlier in MC

Most of energy is deposited in the e.m. calorimeter

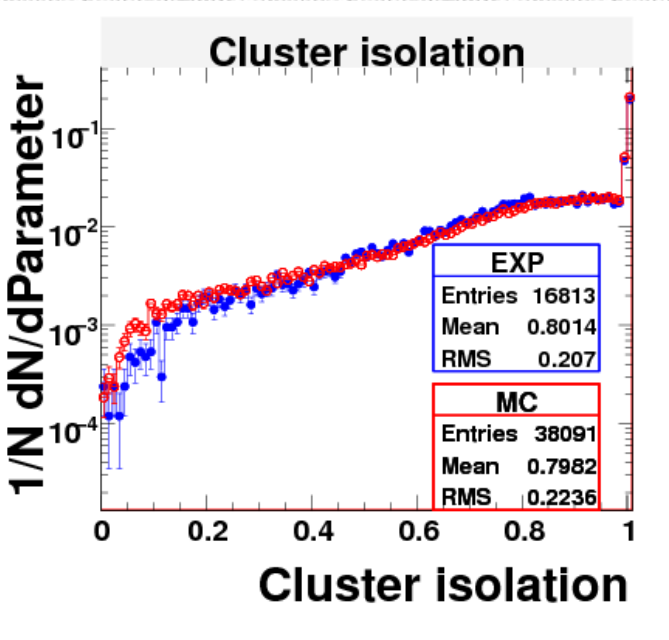
Shower is nearly completely contained in the had. calorimeter

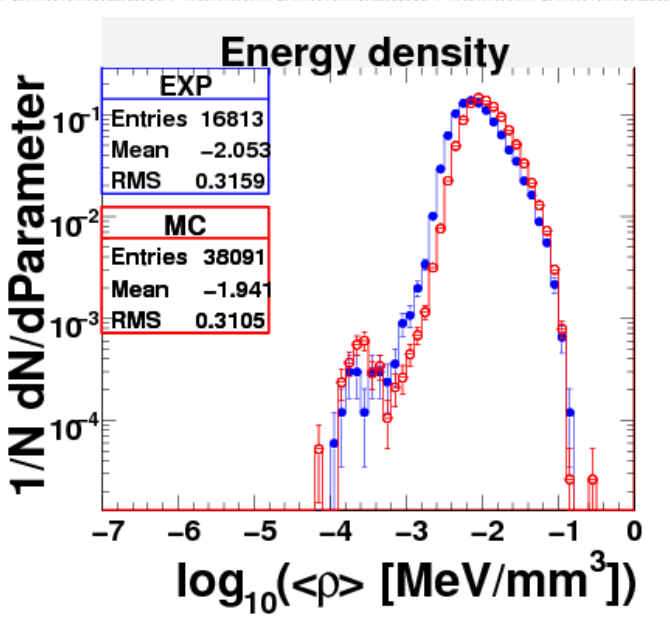






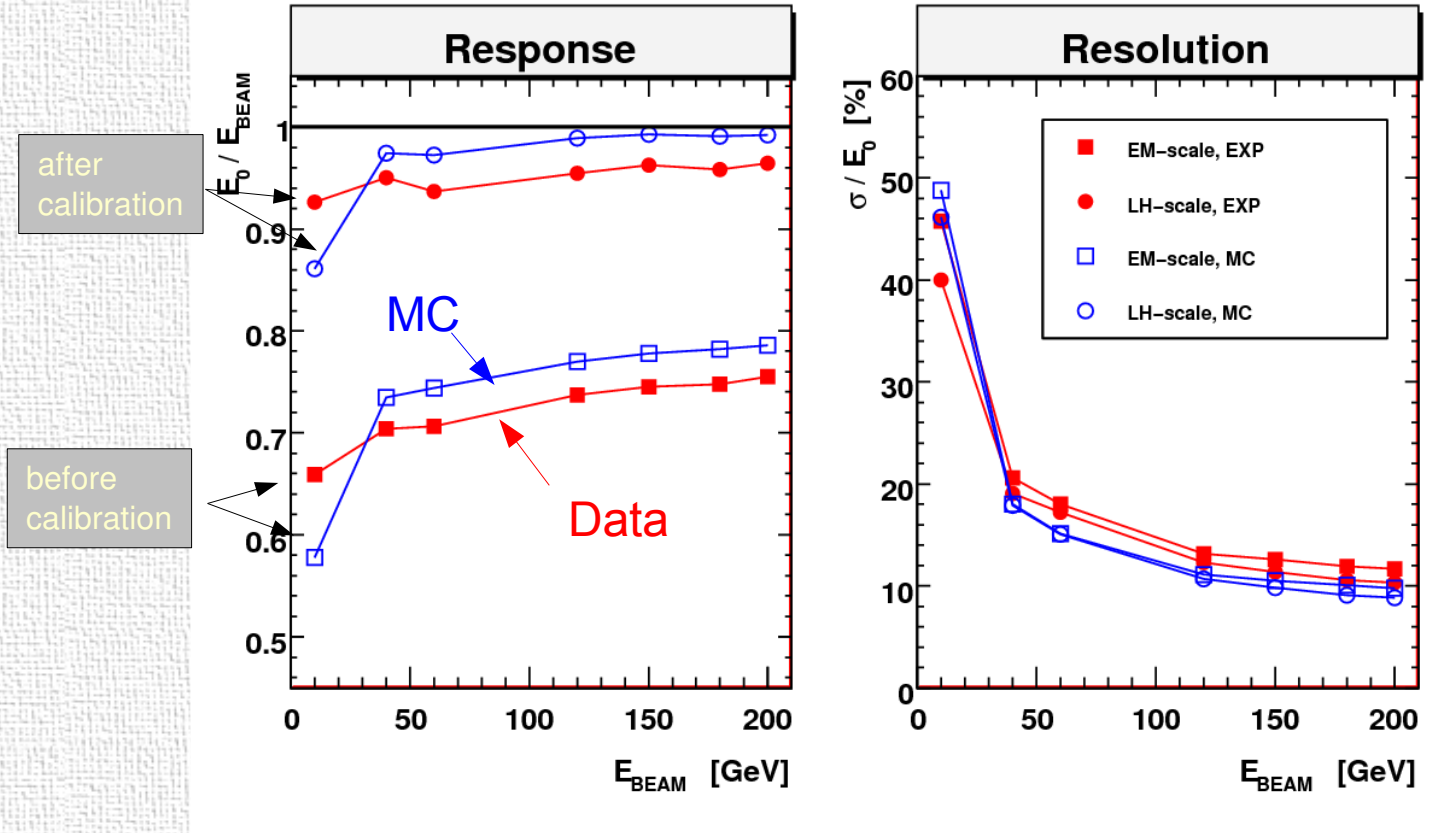
Cluster moments for the endcap region





- Comparison of degree of cluster isolation (left) and average cluster energy density (right) in Monte-Carlo and data.
  - ➔ Slightly denser shower in Monte-Carlo

Linearity and resolution (preliminary) for pions



- Plot shows the linearity (left) and the resolution (right) for 10 ≤ π- ≤ 200 GeV, data and MC, in endcap region (Point D)
  - ➔ Response in Monte-Carlo at e.m. scale level for charged pions is 5% higher, than in the data (this is a bias introduced by QGSP_BERT list). After calibration same difference remains.
  - ➔ In Monte-Carlo after calibration linearity recovered at 2% to 5% level for pion energies larger, than 20 GeV. There is no big improvement in resolution – testbeam specific constants have to be used instead of ATLAS ones (in particular for dead material corrections).

Conclusion

- Local hadronic calibration procedure is a simulation-based technique used in ATLAS to calibrate topological clusters from e.m. scale to particle level

- The validation of this procedure is in progress using ATLAS LAr combined testbeam data (2004)
  - ➔Hadronic calibration constants based on ATLAS geometry have been used

- For pions Monte-Carlo Geant4_9.2_QGSP_BERT does not describe data perfectly
  - ➔We see a standard feature of QGSP_BERT – slightly denser shower, which starts earlier in calo
  - ➔Pion energy response is described within 5%
  - ➔Simulation underestimates data resolution by 20%
  - ➔Longitudinal and lateral shapes of the shower are described quite well
  - ➔Reasonable good description of response for electrons in crack scans
  - ➔Limited acceptance makes results very sensitive to a proper shower description in MC

- Local hadronic calibration is able to restore linearity at 2% for Monte-Carlo
  - ➔e.m. scale for hadrons has to be tuned

- Relative energy resolution is expected to improve by 20%, while it remains the same
  - ➔New testbeam specific set of correction coefficients has to be applied (to account for limited acceptance, and different dead material)

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Backup slides

Topological clusters

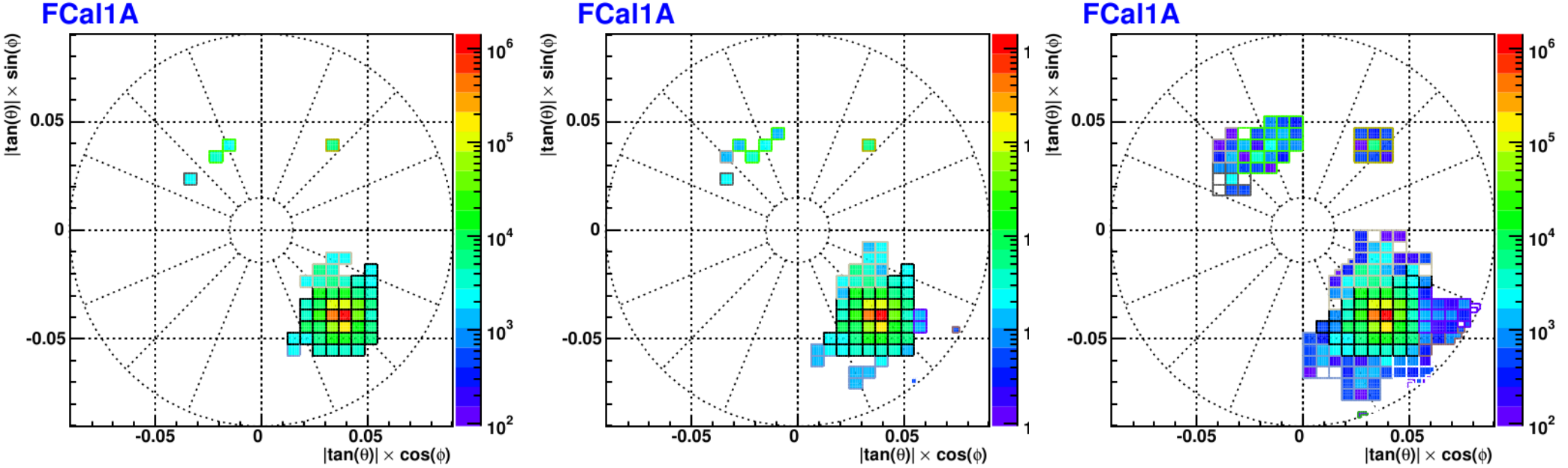
Cluster making algorithm

- form cluster around seed cells with $|E_{cell}| > S \bullet \sigma_{noise}$, S=4
- expand in 3D, add neighbours with $|E_{cell}| > N \bullet \sigma_{noise}$, N=2
- add perimeter cells with $|E_{cell}| > P \bullet \sigma_{noise}$, P=0
- Seed/Neighbour/Perimeter formula = 4/2/0 good for combined beam tests

Cluster splitting algorithm

- split clusters around local maxima with maxima threshold E>500MeV
- one cell can share energy between two clusters
- aim is to have one cluster per isolated $e^{\pm}$,μ,γ, currently $N_{particle}/N_{clusters}$=1.6 in jet context

$|E_{cell}| > 4\sigma_{noise}$ | $|E_{cell}| > 2\sigma_{noise}$ | all cells



Classification

To identify EM and non-EM parts of the shower

Uses following shower shape variables (so-called cluster moments):

λ_{center} cluster barycenter depth in calorimeter

$<\rho_{cell}>$ average cell energy density

High average cell energy density and small calorimeter cluster depth denotes EM nature of the cluster.

4-dimensional phase space for clusters in

$|\eta|$, $E_{cluster}$, $\log10(\lambda_{center})$, $\log10(<\rho_{cell}>)$

is binned and filled with simulated pions in the energy range

$200MeV < E_{cluster} < 2TeV$

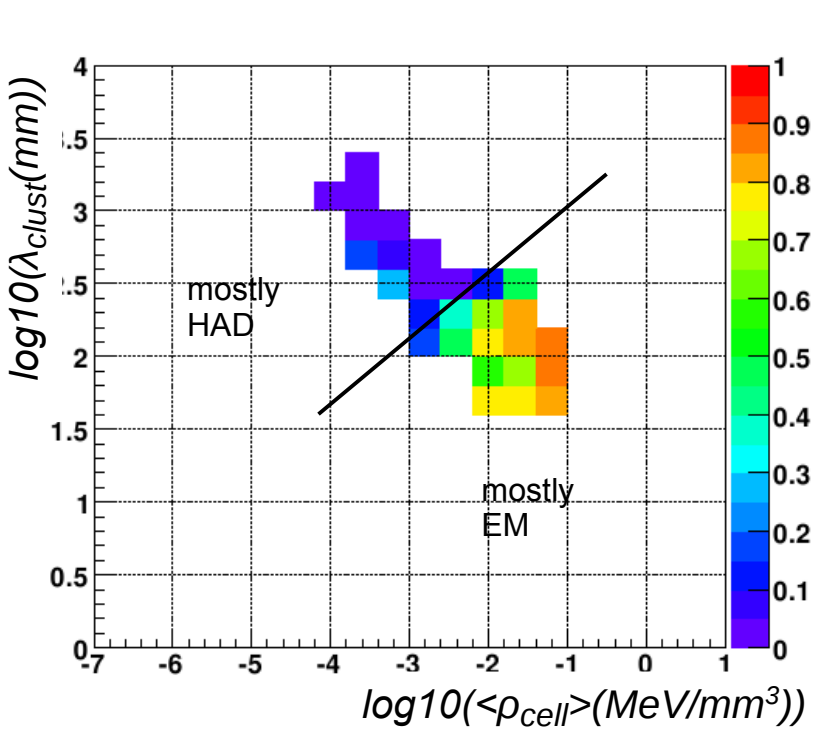


Table of probability for cluster to be EM
$2.0<|\eta|<2.2$, $4GeV \le E_{cluster} < 16$ GeV

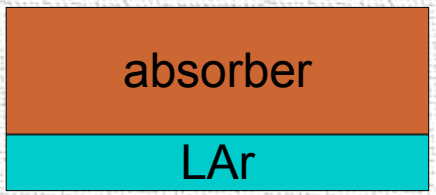
Fraction of neutral and charged pions in given phase-space bin i is used to calculate weight:

$$w_i = n^i_{\pi^0} / \left(n^i_{\pi^0} + 2\ n^i_{\pi^\pm} \right)$$

At reconstruction stage cluster will be treated as electromagnetic if lookup value for $w > 0.5$ at a given cluster phase-space point.

Weighting

Cell weights are derived from true energy deposits in LAr+Absorber (calibration hits) and accounts for invisible energy.



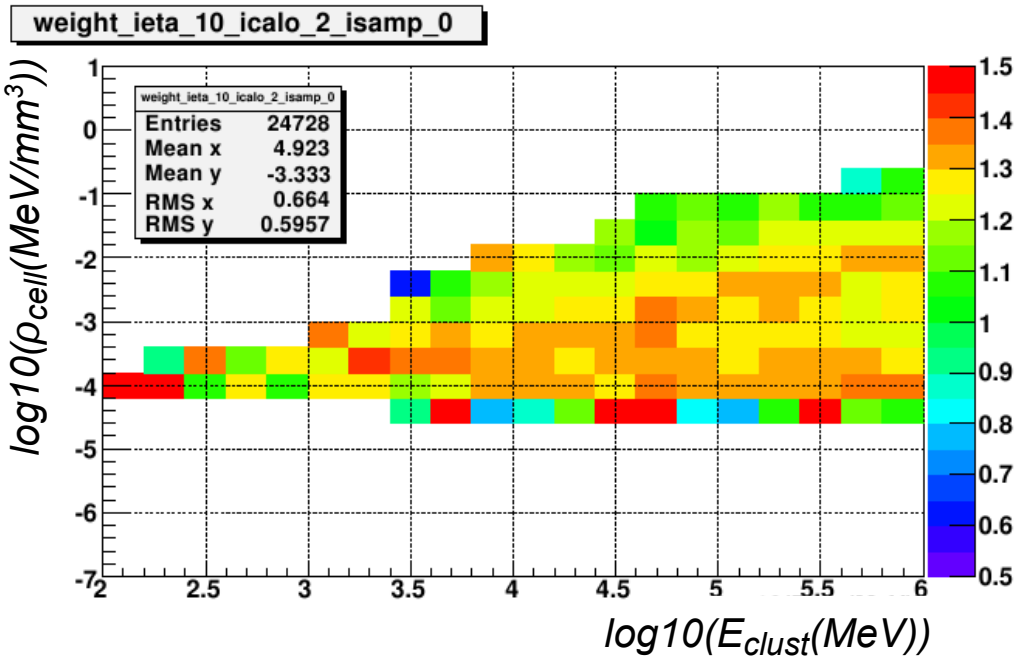
$$E'_{cell} = w \cdot E_{cell},$$

$$w = \left\langle \left(E^{Em}_{cell} + E^{nonEm_{vis}}_{cell} + E^{nonEm_{invis}}_{cell} + E^{escaped}_{cell} \right) / E^{reco}_{cell} \right\rangle$$

calibration hits — *cell signal at em scale (with noise and HV correction)*

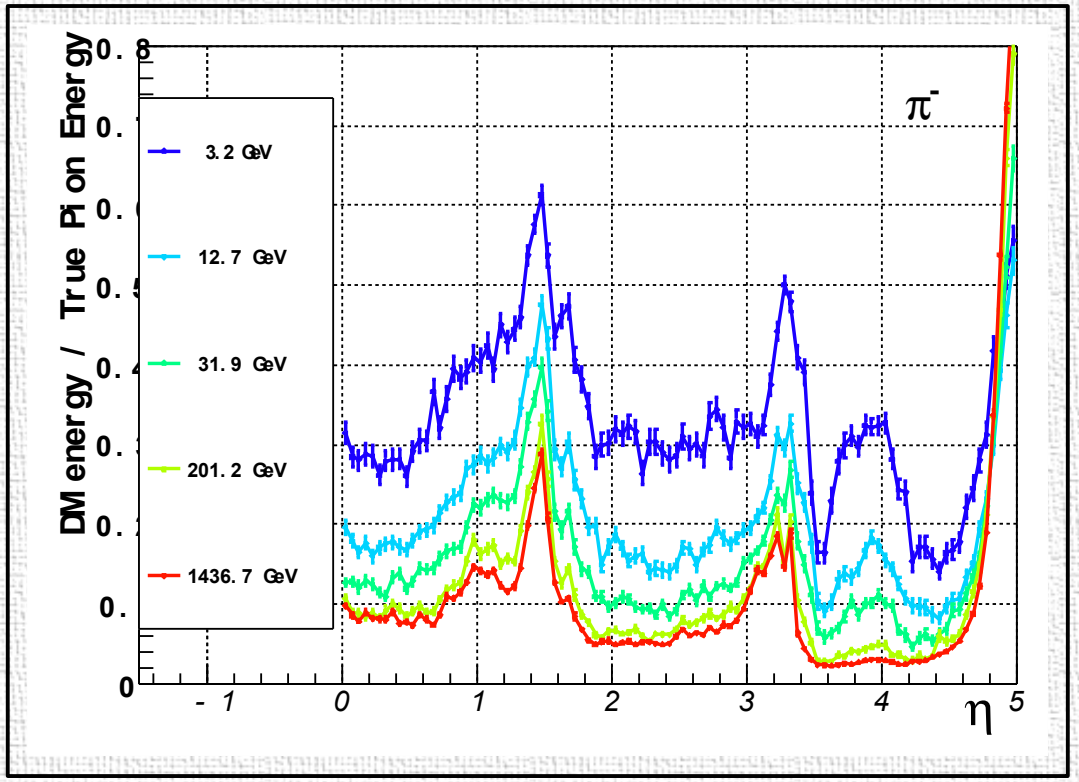
Weights are kept as a function of cluster energy $E_{cluster}$ and cell energy density $\langle \rho_{cell} \rangle$, for different η regions and longitudinal sampling.

Weights are applied only to the clusters classified as hadronic.



Hadronic cell weight table for 2.0<|η|<2.2, HEC layer 1

Dead material correction



Dead material (DM) correction accounts for energy deposited outside of active calorimeter volumes.

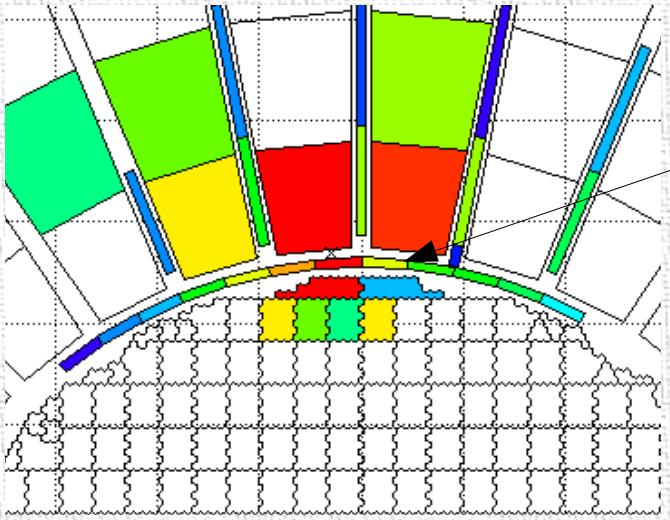
← Average ratio of DM energy to the beam energy versus |η| for charged pions at different energies.

Energy losses outside of calorimeter cell volumes are stored in dead material calibration hits - virtual cells (70000 total) with 0.1x0.1 typical granularity.

Correction is derived for each DM region separately using correlation of DM energy losses (MC) and cluster quantities calculated at electromagnetic scale.

example:
energy lost between EMEC and HEC calorimeters is parametrized as a function

$$\sqrt{E_{EME3} * E_{HEC0}}$$



dead material calibration hit in the crack between HEC and FCAL

Energy in calorimeters in the endcap region (point D)